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# On Theoretical Uncertainties of the $W$ Angular Distribution in $W$ -Pair Production at LEP2 Energies<sup>\*</sup>

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## Abstract

We discuss theoretical uncertainties of the distribution in the cosine of the  $W$  polar angle projected into a measurement of the anomalous triple gauge-boson coupling  $\lambda = \lambda_\gamma = \lambda_Z$  at LEP2 energies for the tandem of the Monte Carlo event generators KoralW and YFSWW3 and for the Monte Carlo event generator RacoonWW. Exploiting numerical results of these programs and cross-checks with experimental fitting procedures, we estimate that the theoretical uncertainty of the value of  $\lambda$  due to electroweak corrections, as obtained at LEP2 with the help of these programs, is  $\sim 0.005$ , about half of the expected experimental error for the combined LEP2 experiments ( $\sim 0.010$ ). We use certain idealized event selections; however, we argue that these results are valid for realistic LEP2 measurements.

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A distribution of the *cosine* of the  $W$  boson production angle  $\theta_W$  is one of the main observables in the  $W$ -pair production process measured by the LEP2 experiments. It is sensitive to the triple gauge-boson couplings (TGCs)  $WWV$ , with  $V = Z, \gamma$  [1–5], particularly to the  $C$ - and  $P$ -conserving anomalous couplings  $\lambda_\gamma, \lambda_Z$  [6]. In this work we present our estimate of the theoretical uncertainties (TU) related to electroweak (EW) corrections in the measurement of the anomalous TGC  $\lambda = \lambda_\gamma = \lambda_Z$  in the  $W$ -pair production at LEP2 energies<sup>1</sup>. It is important to note that we treat the anomalous TGC as a small new-physics effect beyond the consistent Standard-Model prediction, i.e. we introduce the anomalous TGC in the lowest-order matrix element, which is dressed by initial-state radiation, while genuine weak corrections are unaffected by the anomalous TGC. We concentrate on  $\lambda$  in order to keep our analysis as simple as possible and because the value of  $\lambda$  fitted to experimental data depends more strongly on the shape of the  $\theta_W$  distribution than on its total normalization. In fact, while  $\lambda$  is mainly sensitive to the shape of the  $W$  polar angle distribution, it is not particularly sensitive to other single distributions. Using only this variable, we lose only 30% in sensitivity [6]. On the other hand, the analysis of other TGCs would require using more observables.

Our results were obtained using the Monte Carlo (MC) event generators YFSWW3 [8–12] and KoralW [13–15], as well as RacoonWW [16–20]. In YFSWW3 and KoralW, the anomalous TGCs are implemented according to the most general parametrization of ref. [21], and also according to two simplified parametrizations given in ref. [6]. In RacoonWW<sup>2</sup>, the anomalous TGCs involving  $W$  bosons are implemented according to the most general parametrization of ref. [21] in the form given in ref. [6], while those involving only neutral gauge bosons are implemented according to refs. [22, 23].

In the following, we consider the semi-leptonic process  $e^+e^- \rightarrow u\bar{d}\mu^-\bar{\nu}_\mu$ , which belongs to the so-called CC11 class. The corresponding Feynman diagrams constitute a gauge-invariant subset of all 4-fermion final-state processes (see e.g. ref. [24] for more details). We shall study only the leptonic  $W$  polar angle, i.e. the one reconstructed from the four-momenta of the  $\mu^-$  and  $\bar{\nu}_\mu$  (in the actual experiments, the neutrino four-momentum is reconstructed from the constrained kinematical fit, see e.g. refs. [1–4]). The input parameters are the same as in the LEP2 MC Workshop studies performed in 2000 [25]. All the results in this work are given for the centre-of-mass energy  $E_{CM} = 200$  GeV. The results from YFSWW3 are for the leading-pole approximation (LPA) for the double-resonant  $WW$  production and decay of the type advocated in ref. [26], which is implemented in YFSWW3 as an option LPA<sub>a</sub> (see ref. [12] for more details). The results from RacoonWW are based on the double-pole approximation (DPA) as worked out in ref. [18]. In all our numerical exercises we use  $\lambda = \lambda_\gamma = \lambda_Z$ , and all other anomalous couplings are set to zero.

In our analysis we use two different fitting procedures. In the first part of the paper we do direct fits to the  $\cos \theta_W$  distributions with the help of the semi-analytical program KorWan [13, 14, 27]. Since in KorWan one cannot apply any experimental-like cuts, it can

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<sup>1</sup>A similar analysis for the  $W$  mass measurement was done in ref. [7].

<sup>2</sup>The anomalous TGCs are implemented in RacoonWW 1.2, which was released recently (see <http://ltpth.web.psi.ch/racoonww/racoonww.html>).

be used, in principle, only for fitting some idealistic distributions (without cuts), for which good fits (with low  $\chi^2$ ) can be expected. We, however, decided to apply the KorWan fits also to more experimental-like distributions. The results of these fits should be considered only as an independent cross-check for the main fitting procedure, the so-called Monte Carlo parametric fit, presented in the second part of the paper. In this procedure, contrary to the KorWan fits, any event selection criteria can be applied. As such, this fitting procedure can be used for experimental data, which is not the case for the KorWan-based method. Note that the results of the KorWan fits depend on the Monte Carlo errors, and thus on the models used for the Monte Carlo integration. Since the models implemented in KorWan and YFSWW3 are similar, fits of the YFSWW3 distributions yield reasonable results for the shifts in  $\lambda$ . However, since the models implemented in KorWan and RacoonWW are too different to make reasonable fits possible, we do not fit the RacoonWW distributions in the first part of the paper.

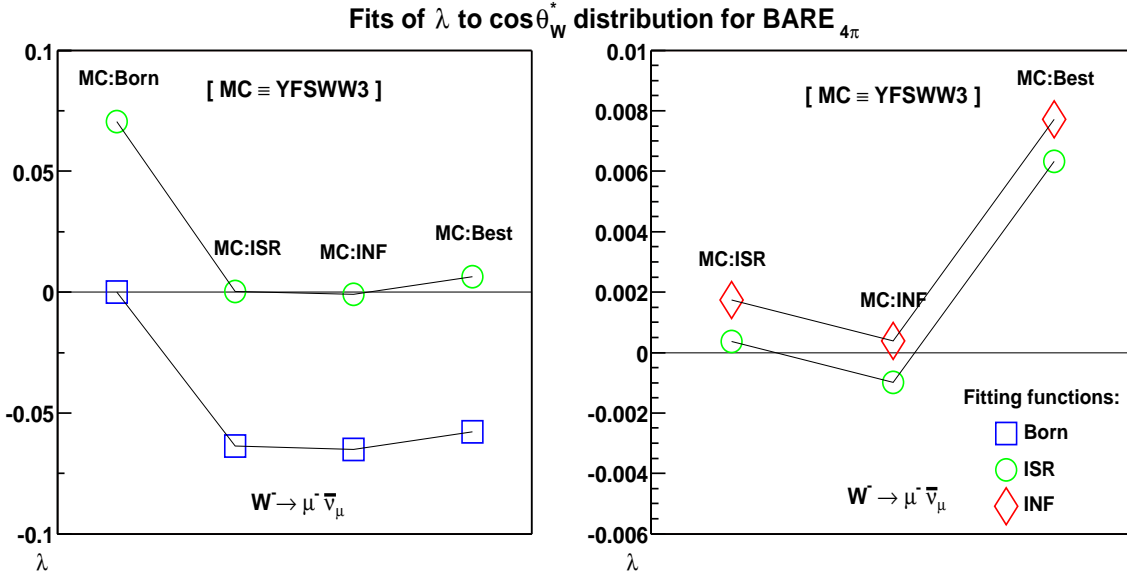


Figure 1: Introductory exercise with YFSWW3, see description in text.

In the first preparatory step, we construct a simple fitting procedure for  $\cos\theta_W^*$ , where the superscript  $*$  means that  $\theta_W$  is evaluated in the  $WW$  rest frame<sup>3</sup>. We “calibrate” the fitting procedure for the  $\cos\theta_W^*$  distribution by using it with the MC data in which we switch on/off the same effects as in the fitting function (FF), typically the initial-state radiation (ISR) and the non-factorizable (NF) corrections, in order to see whether we get agreement in the case of the same effect in the MC data and in the FF. The FF is taken, in all cases, from the semi-analytical program KorWan [13,14,27]<sup>4</sup>. In the YFSWW3 MC and in the fitting function the NF corrections are implemented in the inclusive approximation

<sup>3</sup>More precisely,  $\theta_W^*$  is defined as the angle between the directions of the  $W^-$  in the  $WW$  rest frame and the  $e^-$  beam in the laboratory frame.

<sup>4</sup>The relevant distribution will be available in the next release of KorWan/KoralW.

(denoted by INF in the following) of the so-called screened Coulomb ansatz by Chapovsky and Khoze [28], which is an approximation of the full calculation of the non-factorizable corrections [29–32]. Here, for completeness, we note that in RacoonWW non-factorizable corrections are included beyond the inclusive approximation (see Ref. [18]). In particular, the real-photon non-factorizable corrections (as well as final-state radiation) are contained in the full  $e^+e^- \rightarrow 4f + \gamma$  matrix elements which are used.

One immediate profit of this introductory exercise is that we get an estimate of the size of the ISR and NF effects on the fitted (measured)  $\lambda$  in Fig. 1, which is determined from a two-parameter fit to the  $\cos\theta_W^*$  distribution. In addition to  $\lambda$  we also fit the overall normalization, which is necessary in the presence of cuts in the MC data and/or when the MC model does not correspond exactly to the KorWan model. As a consequence, the fitted values of  $\lambda$  depend on the normalization and on the shape of the distribution. The results of the first exercise, for the BARE $_{4\pi}$  event selection (no photon recombination) and without any cuts (the subscript  $4\pi$  means the full solid-angle coverage), are shown in Fig. 1. Let us explain briefly the notation: **Born** denotes the CC03 Born-level results, **ISR** the ones including the  $\mathcal{O}(\alpha^3)$  LL YFS exponentiation for the ISR as well as the standard Coulomb correction [33], **INF** the above plus the INF correction, and **Best** denotes the best predictions from YFSWW3, i.e. all of the above plus the  $\mathcal{O}(\alpha^1)$  EW non-leading (NL) corrections<sup>5</sup>. In all the MC simulations the input value of  $\lambda$  was 0. The errors of the fitted values due to the statistical errors of the MC results are in all cases  $< 0.001$ .

Let us summarize the observations resulting from Fig. 1:

- The fitted values of  $\lambda$  agree with the input ones, i.e.  $\lambda = 0$ , in the cases when the FF corresponds to the model used in the MC simulations.
- The effects of the ISR are huge,  $\sim 0.07$ .
- The effects of the INF corrections are very small,  $\sim 0.0015$ . This is to be expected since the non-factorizable corrections are strongly suppressed once the invariant masses of the  $W$  bosons are integrated over.
- The effects of the NL corrections are sizeable,  $\sim 0.008$ .

Before we go to the next exercise, let us briefly describe the acceptances/cuts that were used in the MC simulations for the following calculations:

1. All photons within a cone of  $5^\circ$  around the beams were treated as *invisible*, i.e. their momenta were discarded when calculating angles, energies, and invariant masses.
2. The invariant mass of a *visible* photon with each charged final-state fermion,  $M_{f_{ch}}$ , was calculated, and the minimum value  $M_{f_{ch}}^{min}$  was found. If  $M_{f_{ch}}^{min} < M_{rec}$  or if the photon energy  $E_\gamma < 1 \text{ GeV}$ , the photon was combined with the corresponding fermion, i.e. the photon four-momentum was added to the fermion four-momentum

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<sup>5</sup>The  $\mathcal{O}(\alpha^1)$  EW corrections for the  $WW$  production stage in YFSWW3 are based on refs. [34, 35].

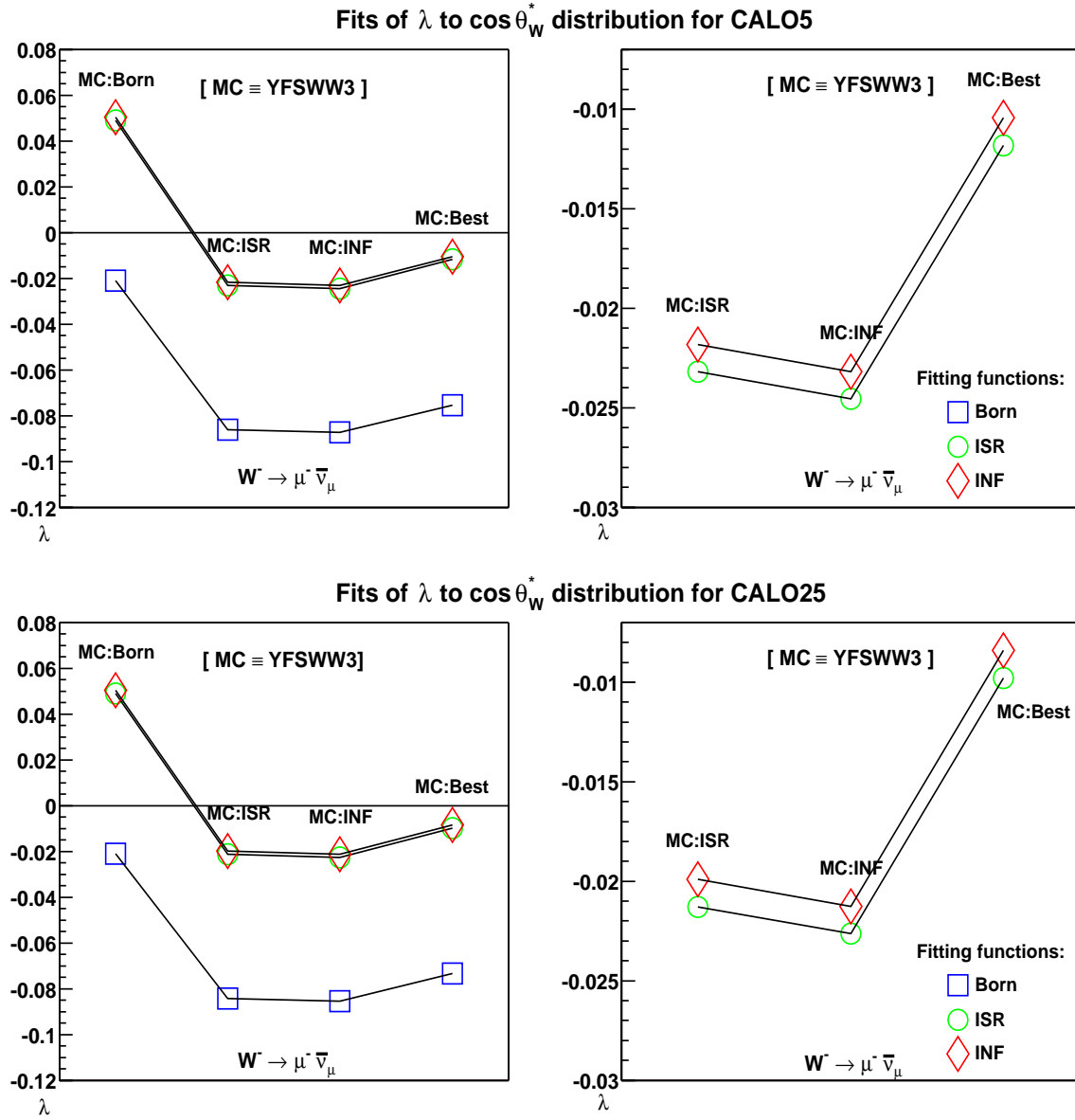


Figure 2: Results for calorimetric-type acceptances from YFSWW3.

and the photon was discarded. In YFSWW3 and KoralW, this was repeated for all *visible* photons, while in RacoonWW there is only one visible photon.

In our numerical tests we used two values of the recombination cut:

$$M_{rec} = \begin{cases} 5 \text{ GeV:} & \text{CALO5,} \\ 25 \text{ GeV:} & \text{CALO25.} \end{cases}$$

Let us remark that we have changed here the labelling of these recombination cuts from the slightly misleading *bare* and *calo* names used in Ref. [25]. They correspond

to our CALO5 and CALO25, respectively. This change allows us to reserve the BARE name for a “truly bare final fermion” event selection (without any recombination).

3. Finally, we required that the polar angle of any charged final-state fermion with respect to the beams be  $\theta_{f_{ch}} > 10^\circ$ .

In the next exercise, presented in Fig. 2, we examine similar effects as in Fig. 1, but now for the calorimetric-type acceptances/cuts: CALO5 and CALO25.

The following observations resulting from Fig. 2 can be made:

- For the calorimetric event selections, the fitted values of  $\lambda$  are shifted by  $\sim -0.02$  with respect to the input ones in the cases when the FF corresponds to the model used in the MC simulations. This can be explained by the fact that the FF of KorWan is for the full angular acceptance while the MC results were obtained with a cut on the charged final-state fermions.
- The size of the ISR is the same as for the BARE event selection, cf. Fig. 1.
- The shift of  $\lambda$  due to the NL corrections increased from  $\sim 0.008$  for BARE to  $\sim 0.011$  for both CALO5 and CALO25.
- The fitted values of  $\lambda$  for CALO5 are slightly different (by  $\sim 0.002$ ) from the corresponding ones for CALO25, but the differences  $\Delta\lambda$  between various models are the same.

From the fits to KorWan, we can conclude that the effects of the NL corrections on  $\lambda$  are sizeable, of the order of the expected experimental precision of the final LEP2 data analysis. Thus, they need to be accounted for in the experimental measurements of the TGCs.

In the second, main part of our study, we follow an alternative fitting strategy for  $\lambda$  in which we do not exploit the angular distribution (fitting function) of KorWan, but instead we rely entirely on the MC results, more precisely, on a simple polynomial parametrization of the normalized angular distribution  $D(\cos\theta_W, \lambda) = \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_W}(\cos\theta_W, \lambda)$  as a function of  $\cos\theta_W$  and  $\lambda$ , determined from running the MC for several values of  $\lambda$ . Since the distribution  $D$  is normalized, the fitted values of  $\lambda$  depend only on the shape. Let us call this method a “Monte Carlo parametric fit”, or the MPF in short, and the MPF fitting function – the MPFF. Once such a MPF with the MPFF is established, then in principle it could be used to quantify a deviation of  $\lambda$  by fitting the MPFF to the experimental angular distribution. Our aim is rather to quantify various components of TU of the SM predictions of the MC tandem KoralW and YFSWW3 and the MC RacoonWW directly in terms of  $\lambda$  (similarly as in the previous method based on KorWan). The main advantage of the MPF is that this can be applied for an arbitrary event selection and any definition of  $\theta_W$ , while any semi-analytical program like KorWan has a strongly restricted choice of the angle definition and kinematic cuts. The MPF method is feasible and not very

difficult in practice because the distribution  $D(\cos\theta_W, \lambda)$  is a very smooth function of its two arguments for LEP2 energies<sup>6</sup>. Another advantage of the MPF will unfold in the following – in fact, we shall be able to get closer to the fitting procedure of the real LEP2 experiments.

Here, we include also the results from RacoonWW. The comparison of YFSWW3 and RacoonWW is very interesting, because the two calculations differ almost in every aspect of the implementation of the ISR, final-state radiation (FSR), NL, and NF corrections. The “ISR” prediction of RacoonWW, which also contains the off-shell Coulomb singularity [32, 36, 37], is exclusively based on the collinear structure-function approach, i.e. all generated photons are collinear to the beams and are thus treated as invisible. In contrast, YFSWW3 generates photons with finite transverse momenta also in the “ISR” version. For the “Best” predictions of RacoonWW, photon radiation in  $\mathcal{O}(\alpha)$  is included via the full matrix elements, and the main differences to YFSWW3 come from two sources. First, RacoonWW does not contain ISR corrections to the non-collinear one-photon emission contribution, in contrast to YFSWW3. Then, while the FSR is generated by PHOTOS [38] in YFSWW3, it is included via the explicit  $e^+e^- \rightarrow 4f + \gamma$  matrix elements in RacoonWW.

How is the MPF realized in practice? We use the following 9-parameter MPFF formula

$$\rho(\cos\theta_W, \lambda) = \frac{D(\cos\theta_W, \lambda)}{D(\cos\theta_W, 0)} = \sum_{i=0}^2 a_i \lambda^i + \cos\theta_W \sum_{i=0}^2 b_i \lambda^i + \cos^2\theta_W \sum_{i=0}^2 c_i \lambda^i, \quad (1)$$

where parameters  $a_i$ ,  $b_i$  and  $c_i$ ,  $i = 0, 1, 2$ , are determined by fitting the  $\rho(\cos\theta_W, \lambda)$  distribution obtained from YFSWW3 or RacoonWW for the three values  $\lambda = -0.2, 0.0, 0.2$ <sup>7</sup>. We have checked that the fitted MPFF: (a) reproduces the MC result of  $\rho(\cos\theta_W, \lambda)$  for any  $\lambda \in (-0.2, 0.2)$  within the fit error of  $\sim 0.001$ , and (b) when the MPFF is used to fit  $\rho(\cos\theta_W, \lambda)$  generated by the MC for any  $\lambda \in (-0.2, 0.2)$  the fitted value agrees, within the fit error, with the input  $\lambda$  used in the MC. Moreover, within fit errors we find  $a_0 = 1$  and  $b_0 = c_0 = 0$  as required. Obviously, the other coefficients  $a_i$ ,  $b_i$  and  $c_i$  are different for every kind of the event selection and angle definition, and the MPF is always a two-step procedure: first we determine the MPFF using the MC, and then we apply it to the results of another MC run (we do not fit experimental data). All the results in the following are obtained for the  $\cos\theta_W^{\text{LAB}}$  distributions, i.e. from now on we use  $\theta_W \equiv \theta_W^{\text{LAB}}$ .

We are now ready to quantify various effects in the  $\cos\theta_W^{\text{LAB}}$  distribution in terms of  $\lambda$  using the MPF procedure. To this end, we define  $\rho_{FD}(\cos\theta_W) = D_1(\cos\theta_W, 0)/D_2(\cos\theta_W, 0)$  where  $D_1$  and  $D_2$  are the normalized angular distributions (for  $\lambda = 0$ ), whose difference we want to quantify and fit this distribution to the MPFF  $\rho(\cos\theta_W, \lambda)$  to obtain  $\Delta\lambda$ . In Table 1, columns 3–5, we show  $\Delta\lambda$  due to the  $\mathcal{O}(\alpha)$  EW NL corrections: in YFSWW3 denoted by “Y: Best–ISR”, in RacoonWW denoted by “R: Best–ISR”, and due to the

<sup>6</sup>The MPF procedure would be less practical at high energies or even at LEP2 for fitting  $M_W$  using an effective  $W$  mass distribution.

<sup>7</sup>The actual fit of  $a_i$ ,  $b_i$  and  $c_i$  is done in two steps, first for each fixed  $\lambda = -0.2, 0.0, 0.2$ , and next for the  $\lambda$  dependence. We have checked that the results do not change if the fit is done in one step.

Fitting procedure		Fitted data			
Fitting function	Accept.	Y: Best–ISR	R: Best–ISR	Best: R–Y	Accept.
1. KorWan	BARE	0.0114 (6)	—	—	CALO5
2. KorWan	BARE	0.0115 (6)	—	—	CALO25
3. MPF: Y-ISR	CALO5	0.0112 (7)	0.0097 (8)	0.0008 (9)	CALO5
4. MPF: Y-ISR	CALO5	0.0115 (7)	0.0161 (8)	0.0008 (9)	CALO25
5. MPF: R-ISR	CALO5	0.0112 (7)	0.0097 (8)	0.0008 (9)	CALO5
6. MPF: R-ISR	CALO5	0.0115 (7)	0.0161 (8)	0.0008 (10)	CALO25
7. MPF: Y-Best	CALO5	0.0113 (7)	0.0098 (8)	0.0008 (10)	CALO5
8. MPF: Y-Best	CALO5	0.0116 (7)	0.0162 (8)	0.0008 (9)	CALO25
9. MPF: R-Best	CALO5	0.0110 (7)	0.0096 (8)	0.0007 (9)	CALO5
10. MPF: R-Best	CALO5	0.0113 (7)	0.0158 (8)	0.0008 (9)	CALO25
11. MPF: KoralW	ALEPH	0.0118 (7)	0.0103 (9)	0.0008 (10)	CALO5
12. MPF: KoralW	ALEPH	0.0122 (7)	0.0172 (9)	0.0009 (10)	CALO25

Table 1: The shifts on  $\lambda$  from various fits. We use the abbreviations: Y=YFSWW3 and R=RacoonWW. The numbers in parentheses are the fit errors corresponding to the last digits of the results.

difference RacoonWW–YFSWW3 in their “Best” modes, denoted by “Best: R–Y”. In the first two rows of Table 1, we include for the purpose of “backward compatibility”  $\Delta\lambda$  obtained by using the fitting procedure employing the FF of KorWan (constructed originally for BARE<sub>4 $\pi$</sub> ). Rows 3–12 in Table 1 show the results of the MPF procedure. As already stressed, the type of the MPF is defined by the variant of the MC and the type of the event selection, which are indicated in the first and second columns. In rows 3 and 4 of Table 1, we use the MPFF determined from the MC run of “Y-ISR”, i.e. the MPFF was constructed using the results from YFSWW3 in the “ISR” mode (described above). The similar MPFF from RacoonWW, denoted by “R-ISR” was used to obtain the results in rows 5 and 6. In rows 7 and 8 “Y-Best” denotes the MPFF constructed from the run of YFSWW3 in the “Best” mode, and the similar one for RacoonWW corresponds to rows 9 and 10 (“R-Best”). The type of the event selection (CALO5 or CALO25) in the MC data is indicated in the last column. We use the MPFFs with the coefficients for CALO5 as it gives practically the same results for the fitted  $\lambda$  as the ones for CALO25. We see that all the results of the above five MPFs are consistent with each other, and for YFSWW3 they also agree quite well with the results of the fits employing the FF of KorWan.

The results in Table 1 show that the NL corrections influence  $\lambda$  considerably; they shift  $\lambda$  by  $-0.0096$  to  $-0.0172$  with respect to the ISR-level predictions, which is comparable to the expected final experimental precision on this TGC at LEP2. The large differences in the shifts of  $\lambda$  for “R: Best–ISR” between CALO5 and CALO25 originate from the fact that the “ISR” prediction of RacoonWW includes only collinear photons and thus is not influenced by photon recombination, in contrast to the “Best” prediction of RacoonWW and the “ISR” and “Best” predictions of YFSWW. The results of Table 1 demonstrate



that the NL corrections have to be included in the respective data analyses. On the other hand, the differences between the “Best” predictions of RacoonWW and YFSWW3 are very small,  $< 0.001$ . This is important as the two programs differ in many aspects of the implementation of various effects. The good agreement between these programs is an indication that the effects on  $\lambda$  due to the used approximations and the missing higher-order corrections should be small. This will be further investigated in the following.

Last but not least, the MPFF can also be defined for the true LEP2 acceptance. In rows 11 and 12 we exploit MPFFs that use  $a_i$ ,  $b_i$  and  $c_i$  determined for the real-life ALEPH acceptance, which are denoted as “ALEPH”. The ALEPH selection and reconstruction efficiencies for jets and leptons are described in refs. [1,39] (typically, the lepton acceptance reaches  $|\cos\theta| = 0.95$ ). Again the values of the fitted  $\Delta\lambda$  are about the same as in the previous exercises for the “academic” event selections. This important cross-check makes us confident that our estimates of the TU of  $\lambda$  are indeed relevant to the real-life LEP2 measurements.

Effect	Acceptance	$\Delta\lambda$
1. Best – ISR	BARE <sub>4<math>\pi</math></sub>	0.0108 (7)
	CALO5 <sub>4<math>\pi</math></sub>	0.0110 (7)
2. ISR <sub>3</sub> – ISR <sub>2</sub>	BARE <sub>4<math>\pi</math></sub>	0.0001 (2)
	CALO5 <sub>4<math>\pi</math></sub>	0.0001 (2)
3. FSR <sub>2</sub> – FSR <sub>1</sub>	BARE <sub>4<math>\pi</math></sub>	0.0001 (3)
	CALO5 <sub>4<math>\pi</math></sub>	0.0001 (3)
4. 4 $f$ -background corr. (Born)	CALO5	0.0021 (3)
	CALO25	0.0021 (3)
5. 4 $f$ -background corr. (with ISR)	CALO5	0.0005 (3)
	CALO25	0.0005 (3)
6. EW-corr. scheme: $(B) - (A)$	CALO5	0.0006 (9)
	CALO25	0.0006 (9)
7. LPA <sub>b</sub> – LPA <sub>a</sub>	CALO5	0.0017 (9)
	CALO25	0.0018 (9)

Table 2: The shifts on  $\lambda$  from various effects, obtained with YFSWW3 and KoralW. See the text for more details.

In Table 2, we present the results of the  $\lambda$ -shifts due to switching on/off various effects in YFSWW3 and KoralW. They were obtained with the MPFF constructed with YFSWW3-Best for CALO5. The subscript  $4\pi$  in the acceptance denotes the full solid-angle coverage. In row 1, we show the results of the MPF for the NL correction in YFSWW3, but for acceptances slightly different from the ones in Table 1, namely for BARE<sub>4 $\pi$</sub>  (no photon recombination) and CALO5<sub>4 $\pi$</sub>  (similar to CALO5, but without cuts 1 and 3). These results agree very well with the corresponding results in Table 1 for CALO5 and CALO25 (cf. column 3). This shows that the value of  $\lambda$  is not very sensitive to the choice of cuts and acceptances. Rows 2 and 3 contain the results of switching off

the 3rd order ISR and the 2nd order FSR corrections, respectively. Both these effects are negligible at LEP2 in terms of the  $\lambda$ -shifts. The  $4f$ -background corrections<sup>8</sup> are investigated in rows 4 and 5. While a  $4f$ -background contribution at the Born level induces a shift on  $\lambda$  of  $\sim 0.002$ , it gives a negligible effect when it is combined with the ISR. This is because the ISR affects the  $\cos\theta_W^{\text{LAB}}$  distribution in a way opposite to that of the  $4f$ -background, which leads to large cancellations of the latter effect. Then we investigate the uncertainties of the NL corrections due to different schemes for the EW effective couplings (they account for some parts of higher-order EW corrections): the so-called schemes (A) and (B) in YFSWW3 [12] (row 6), and due to the different LPA approaches: LPA<sub>a</sub> versus LPA<sub>b</sub> [12] (row 7). While the effects on  $\lambda$  of the differences between schemes (A) and (B) are negligible (below the fit errors), the ones due to the LPA variation are  $\sim 0.002$  – this can be regarded as the LPA uncertainty in YFSWW3.

Effect	Acceptance	$\Delta\lambda$
1. Best – ISR	CALO5	0.0096 (8)
	CALO25	0.0158 (8)
2. Off-shell Coulomb effect	CALO5	0.0001 (10)
	CALO25	0.0001 (10)
3. $4f$ -background corr. (Born)	CALO5	0.0029 (10)
	CALO25	0.0029 (10)
4. $4f$ -background corr. (with ISR)	CALO5	0.0008 (10)
	CALO25	0.0008 (10)
5. On-shell projection	CALO5	0.0003 (10)
	CALO25	0.0003 (10)
6. DPA definition	CALO5	0.0005 (10)
	CALO25	0.0005 (10)

Table 3: The shifts on  $\lambda$  from various effects, obtained with RacoonWW. See the text for more details.

In Table 3, we show results of the  $\lambda$ -shifts due to switching on/off various effects in RacoonWW, as obtained with the MPFF constructed with RacoonWW-Best for CALO5. In row 1, we give the shifts between the “Best” and “ISR” modes of RacoonWW. These shifts are due to the NL electroweak corrections, including, in contrast to the numbers from YFSWW3 in Table 2, also the effects of non-collinear photon emission. Row 2 exhibits the results of switching off the off-shellness of the Coulomb singularity. This effect is negligible, since the energy is not in the threshold region and the Coulomb singularity affects mainly the normalization and thus cancels in  $D$  and  $\rho$ . The effect of the  $4f$ -background diagrams without and with the corresponding ISR (rows 3 and 4) is consistent with the corresponding results in Table 2. Finally, we study the uncertainties

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<sup>8</sup>The complete Born-level  $4f$  matrix element in KoralW was generated with the help of the GRACE2 package [40].

of the NL corrections due to different definitions of the DPA in RacoonWW (rows 5 and 6) [18]. These effects are smaller than the corresponding effects seen in row 7 of Table 2. This is because, in RacoonWW, only the virtual corrections are treated in DPA, while in YFSWW3 also the real corrections feel the LPA.

ALEPH MPFF		Fitted data			
Channel	Acceptance	Y: Best–ISR	R: Best–ISR	Best: R–Y	Acceptance
$\mu\nu_\mu qq$	TRUE	0.0118 (7)	0.0102 (9)	0.0008 (10)	CALO5
		0.0121 (7)	0.0170 (9)	0.0009 (10)	CALO25
	RECO	0.0118 (7)	0.0103 (9)	0.0008 (10)	CALO5
		0.0122 (7)	0.0172 (9)	0.0009 (10)	CALO25
$e\nu_e qq$	TRUE	0.0119 (7)	0.0103 (9)	0.0008 (10)	CALO5
		0.0122 (7)	0.0172 (9)	0.0009 (10)	CALO25
	RECO	0.0119 (7)	0.0103 (9)	0.0008 (10)	CALO5
		0.0123 (7)	0.0172 (9)	0.0009 (10)	CALO25
$\tau\nu_\tau qq$	TRUE	0.0115 (7)	0.0100 (8)	0.0008 (10)	CALO5
		0.0118 (7)	0.0166 (8)	0.0009 (10)	CALO25
	RECO	0.0107 (6)	0.0091 (8)	0.0007 (9)	CALO5 <sub>RECO</sub>
		0.0109 (6)	0.0152 (8)	0.0008 (9)	CALO25 <sub>RECO</sub>
$qqqq$	TRUE	0.0118 (7)	0.0102 (9)	0.0008 (10)	CALO5
		0.0120 (7)	0.0169 (9)	0.0009 (10)	CALO25
	RECO	0.0094 (6)	0.0081 (7)	0.0007 (8)	CALO5 <sub>RECO</sub>
		0.0096 (6)	0.0132 (7)	0.0008 (8)	CALO25 <sub>RECO</sub>

Table 4: The results for  $\lambda$  shifts for the fits using the ALEPH fitting functions obtained at the parton level (TRUE) and with the full detector reconstruction (RECO) for various channels. The subscript RECO for some CALO5 and CALO25 acceptances means that the reconstruction effects were also included in the corresponding MC data (see the text for details). The fitted data are always for the channel  $\mu^- \bar{\nu}_\mu u \bar{d}$ . We use the abbreviations: Y=YFSWW3 and R=RacoonWW.

In order to see whether our results can be extended also to other channels, we performed the following exercise. Using simulated data at the parton level (denoted as TRUE) and with the full ALEPH detector reconstruction (denoted as RECO) for the channels  $\mu\nu_\mu qq$ ,  $e\nu_e qq$ ,  $\tau\nu_\tau qq$  and  $qqqq$ , we constructed eight MPFFs – two MPFFs per channel. Then we fitted these functions to our MC data, the same as in Table 1, for the channel  $\mu^- \bar{\nu}_\mu u \bar{d}$ . The results of these fits for all the TRUE-level fitting functions and for the  $\mu\nu_\mu qq$  and  $e\nu_e qq$  RECO-level ones are shown in Table 4. As one can see, all the TRUE-level results are consistent with each other and agree with the ones for the YFSWW3 and RacoonWW MPFFs (cf. Table 1, rows 3–10). The RECO-level results agree very well with the TRUE-level ones for the channels  $\mu\nu_\mu qq$  and  $e\nu_e qq$ . The above results show that the experimentally reconstructed distributions of  $\cos \theta_W$  for the channels  $\mu\nu_\mu qq$  and  $e\nu_e qq$  are very similar to the parton-level ones and also to each other, which in our

exercise resulted in almost identical fitting functions. This leads us to the conclusion that our previous findings for the channel  $\mu\nu_\mu qq$  can be extended to the channel  $e\nu_e qq$ .

For the  $\tau\nu_\tau qq$  and  $qqqq$  channels, the reconstructed distributions differ considerably from the TRUE-level ones. We have checked that fitting the RECO-level MPFF from the  $qqqq$  ( $\tau\nu_\tau qq$ ) channel to our MC data results in the shifts of  $\lambda$  which are by  $\sim 100\%$  ( $\sim 25\%$ ) larger than the corresponding ones for the TRUE-level MPFF (these results are not shown in Table 4). Thus, the parton-level MC data are not appropriate for estimating the shifts of  $\lambda$  in the real-life experimental measurements for these channels. In order to obtain realistic effects, these data have to be processed through the full detector simulation. Instead of feeding our MC events into the full ALEPH reconstruction generator, we applied so-called transfer matrices to the MC  $\cos\theta_W^{\text{LAB}}$  distributions. A transfer matrix gives the probability for an event generated in a TRUE  $\cos\theta_W^{\text{LAB}}$  bin to be found in a given RECO bin. This takes into account non-diagonal terms induced by the ALEPH detector effects (jet resolution, jet pairing, jet charge, and  $\tau$  reconstruction) [1]. The appropriate transfer matrices for these channels were constructed using the Monte Carlo samples generated within the full ALEPH detector simulation environment [41]. Then, we used such experimental-like distributions in the MPFs with the RECO-level fitting functions. In these fits we used appropriate error (covariance) matrices, taking into account correlations between the bins and between the transfer-matrix elements. The results for these two channels at the RECO-level complete Table 4 (they are denoted by the subscript RECO attached to the respective acceptance in the last column). As can be seen, the values of the  $\lambda$  shifts are close to the corresponding TRUE-level results. We also checked that this method did not affect the  $\mu\nu_\mu qq$  and  $e\nu_e qq$  channels, as expected. Therefore our conclusions for the TU of  $\lambda$  in the  $\mu^-\bar{\nu}_\mu u\bar{d}$  channel can be applied also to the  $\tau\nu_\tau qq$  and  $qqqq$  channels in the realistic experimental analyses.

From the above numerical exercises and the accompanying discussion, we come to the following conclusions:

- The non-leading EW corrections cause shifts of  $\lambda = \lambda_\gamma = \lambda_Z$  at the level of 0.01–0.02, which is comparable to the combined experimental accuracy for this anomalous TGC at LEP2. Thus, these corrections have to be taken into account in the experimental analyses.
- The comparisons between YFSWW3 and RacoonWW and the tests of various modes/options in both programs (cf. Tables 2 and 3) allow us to estimate the EW theoretical uncertainty in  $\lambda$ . We use the largest shifts found in these comparisons and apply a safety factor of 2 to account for the  $\sim 30\%$  sensitivity loss due to the single-distribution fit and for possible higher-order effects missing in both programs.

From this we estimate the EW theoretical uncertainty in  $\lambda$  of the MC tandem KoralW&YFSWW3 and of the MC program RacoonWW to be  $\sim 0.005$  at LEP2 energies, which is  $\sim 1/2$  of the expected combined experimental error.

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